

## SAGE at 30

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As you receive this issue of *The Leading Edge* the Summer of Applied Geophysical Experience (SAGE) will be starting our 30th field season. SAGE is a unique educational program that combines teaching and research as a partnership between universities, industry, government agencies and professional societies. SAGE includes a four-week period based in Santa Fe, New Mexico and one-week workshop in the following January for undergraduates, at San Diego State University, which allows us to enhance their research experience. We teach the principles and applications of refraction and reflection seismics, magnetics, gravity, GPS, several electromagnetic (EM) methods and ground-penetrating radar (GPR) in a field-based, hands-on setting. The central research activity of SAGE is the acquisition and interpretation of geophysical field data. Students learn geophysics by doing geophysics—a discovery oriented approach.

Over 730 advanced undergraduate students, graduate students from both large and small schools from many countries, and qualified professionals have attended SAGE, many of whom have gone on to become leaders in academia, industry, and government. Since 1990 we have involved New Mexico Native American students in seven days of the SAGE program to provide them with an introduction to the Earth sciences, geophysics and field work. In recent years, college undergraduate and high school students have come from the Pueblo de Cochiti and Santo Domingo Pueblo. They were selected by their tribes and presented the results of their experience to their families and elders. The interaction of the SAGE students and faculty with the Native American students and their advisors also provides a very positive cultural experience for everyone.

The primary goal of SAGE is to actively engage students in all phases of applied geophysical research. We begin with an introduction to the scientific principles of each geophysical method, how and why they are applied to various geologic problems and related societal needs. This lecture phase of the program includes interactive discussions on the objectives of the field research, the geophysical techniques to be applied and the rationale of how the data will be collected, and geological field trips to establish the context for the geophysical field work (Figure 1). Evening lecture series from professionals in industry and government, some of whom are former SAGE students, provide perspective on a career as a professional geophysicist.

Lectures and discussions are followed by data acquisition, data assessment/processing, and analysis/interpretation using

modern equipment and software. Students are closely guided by faculty, teaching assistants, and industry visitors to analyze and interpret data they collect. The interpretation phase is enhanced through a two-tier team effort leading to oral and written presentations patterned after the SEG Annual Meeting and *Expanded Abstracts*, respectively. Each student is part of a team focused on a specific geophysical technique and an integration team that synthesizes the combined results of various methods. Increasingly, SAGE students present their findings at professional meetings and forums; SEG students can often be found presenting their work at AGU, SAGEEP and SEG annual meetings.

Field problems have included characterizing buried waste, mapping archaeological sites, and studying tectonic structure and water resources of the Rio Grande rift. In 2011 we pursued three field studies: continuing investigation of the Pueblo San Marcos Archaeologic Preserve, defining the eastern edge of the Santo Domingo Basin, and the exploring the possibility of a geothermal resource at the Caja del Rio area of the Española Basin northwest of Santa Fe.

### Scientific highlights

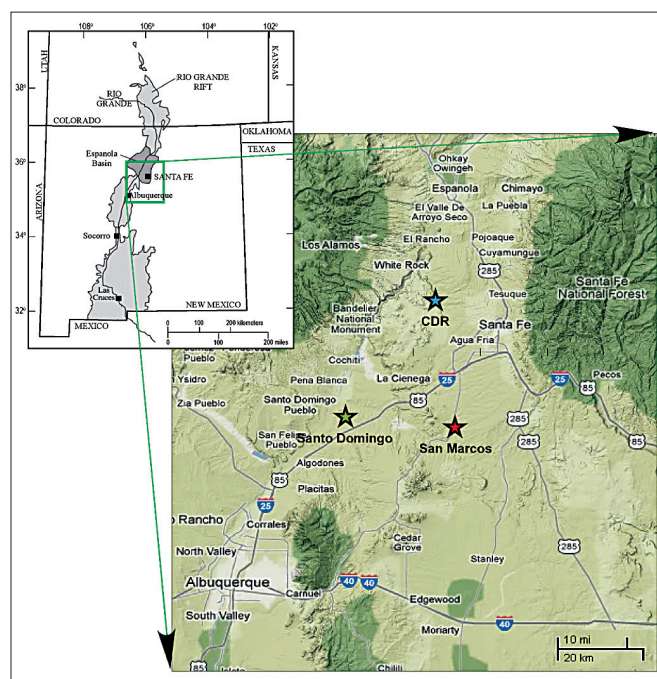
**San Marcos Pueblo Archaeological Site.** Since 2004 we have investigated the archaeology, local geology (Hinz et al., 2008) and hydrogeology (Ferguson et al., 2011) of the Pueblo San Marcos archaeological site using seismic refraction, EM, GPR and magnetic methods. Seismic refraction data (Figure 3a; lines 9, 15, 17, and 18) were chosen to map the geologic structure of the site to better understand the hydrology of San Marcos. The site “basement” is the Eocene Galisteo formation (shown in yellow). The Pliocene Ancha formation (shown in green) overlies the Galisteo. The Ancha is an excellent aquifer that is recharged by snow melt at the mountain front several kilometers away. Overlying Pleistocene terraces seal the aquifer, but are locally eroded away on the West side of the site. (Figure 3b) The springs produced by this exposure would have been a very significant motivation for the settlement of the Pueblo San Marcos. The presence of the Ancha aquifer and springs is unique in the surrounding area. The velocity models obtained by detailed modeling of the refraction data show the importance of the topography and layering at San Marcos as controls on groundwater flow and the locations of springs.

**Santo Domingo Basin.** The active late Cenozoic Rio Grande rift of the south-western U. S. consists of several right-



**Figure 1.** (a) George Jiracek giving a lecture. (b) Scott Baldrige conducting a field trip. (c) The ION/INOVA vibroseis ready for field work.

stepping, faulted basins separated by accommodation zones. SAGE has conducted several geophysical surveys to investigate the structure and evolution of the San Francisco-La Bajada-Hagan accommodation zone (Figure 4) 30 km southwest of Santa Fe. We chose this area because it is in a structurally complex part of the rift, consisting of a small sub-basin (Hagan basin) and plunging ramps, where north-trending enechelon basin-bounding San Francisco and La Bajada faults transfer crustal extension laterally between the larger Española (north) and Albuquerque (south) rift basins. Our



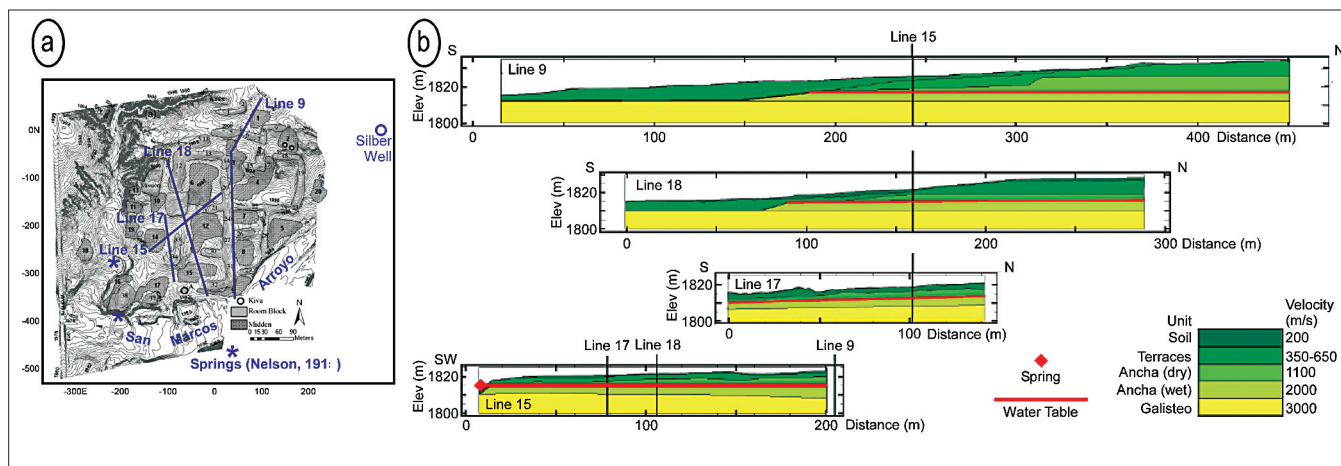
**Figure 2.** Map depicting SAGE survey areas.

continuing work helps define multiple structural elements, partly buried by basin-filling sediments. Our overall goal is to infer kinematic development, linkages among faults, growth history, and possible prerift structural controls (Baldrige et al., 2010).

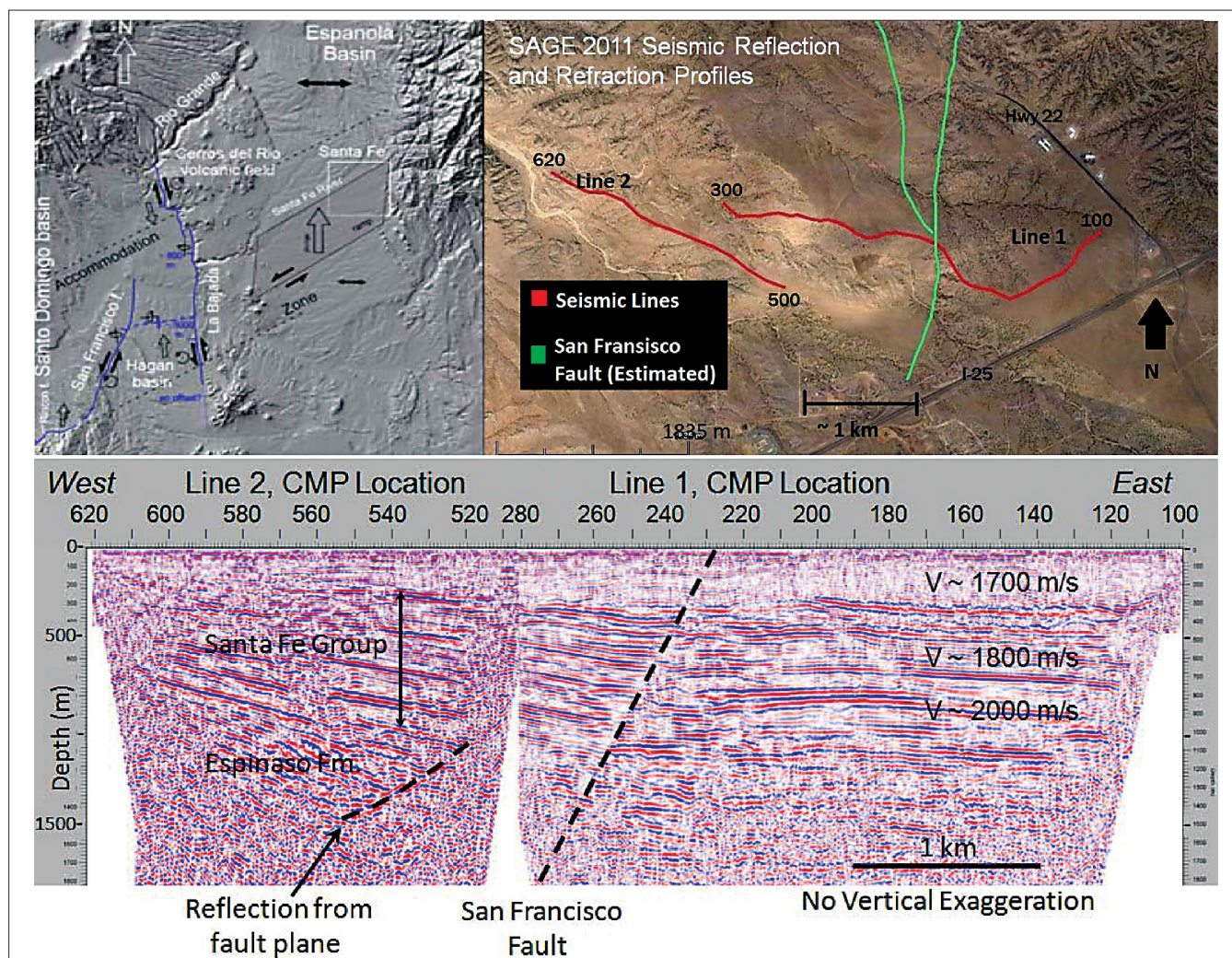
In 2011 SAGE collected seismic and gravity data across the San Francisco Fault. An interpreted CMP stacked seismic section (not migrated) is shown in Figure 4 (Braile et al., 2011). However, our analysis of migration of this fault plane reflection indicates that the true dip of the fault is close to 60°. Another observation from the reflection record section is that the shallow sedimentary layers dip into the fault and thicken toward the fault, indicating that the fault was active during the time of deposition of these units. The seismic reflection signature of the fault on line 1 does not show obvious offsets of reflectors. The lack of clear offsets is likely due to the oblique angle of the recording profile near the surface location of the fault. However, the CMP stacked seismic sections image the San Francisco fault as a marked change in dip of the reflectors at the location of the interpreted fault. The wide-angle reflection from the fault plane seen on line 2 is also consistent with the inferred location of the San Francisco fault and the ~60° dip. The fault signatures, actual reflection from fault plane on line 2, and the fault indicated by abrupt change of dip of the reflectors on line 1, are from the same fault; the reflection on line 2 is an unmigrated wide-angle reflection from the fault plane.

**Caja Del Rio Geothermal Prospect.** In 2011 a pilot project was undertaken to assess the geothermal potential of an area ~25 km northwest of Santa Fe along the eastern edge of the Caja del Rio (CDR) volcanic field (Biagini et al., 2011; Jiracek et al., 2011). Volcanism from 1.14–2.8 Ma has been mapped from more than 50 exposed vents within the CDR (Thomson





**Figure 3.** (a) The topographic base map for the San Marcos Pueblo archaeological site is shown with 0.25-m contour interval. The collapsed room blocks are clearly visible as linear mounds several meters high. The locations of historically persistent springs are indicated by the red \* symbols and the Sibling well in the NE corner is active. (b) The 2D velocity models corresponding to lines 9, 15, 17, and 18 are shown.



**Figure 4.** (top) Regional and detailed maps of the SAGE 2011 field area showing the locations of the seismic profiles. Detailed gravity measurements were also made along the two profiles. (bottom) Interpreted SAGE 2011 west-to-east CMP-processed and stacked seismic reflection record section. Approximate stacking velocities are shown on the line 1 section.



et al., 2006), high temperatures reported in deep-water wells, together with elevated  $3\text{He}/4\text{He}$  ratios in groundwater (Manning, 2009) and numerous, rift-related faults are suggestive of a high-temperature magmatic/mantle component in the groundwater (Johnson et al., 2008). Extrapolation of measured temperature gradients provide estimates of nearly  $200^\circ\text{C}$  within the  $>2$  km-deep sedimentary basin adjacent to the CDR, and temperatures above  $200^\circ\text{C}$  in the impermeable basement at  $<4$  km depth. The latter estimate meets a criterion used to define high-grade enhanced geothermal systems.

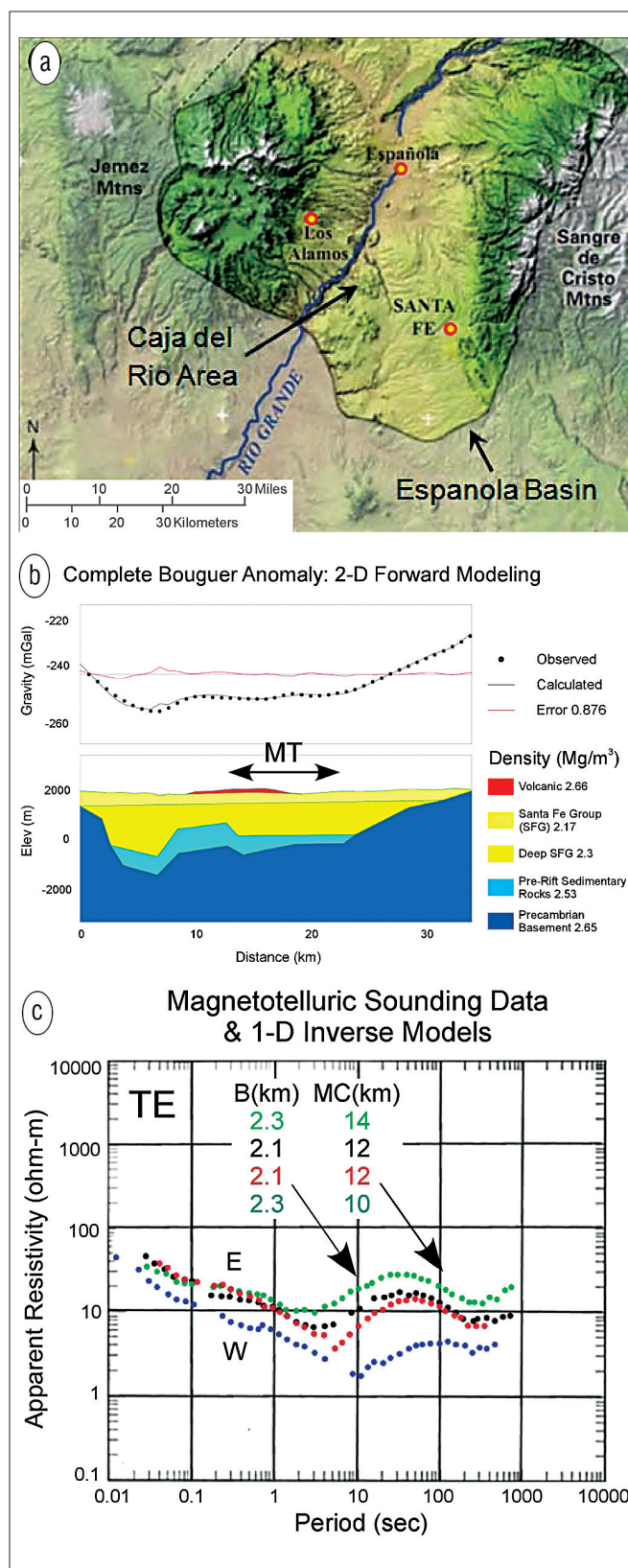
SAGE 2011 gravity and magnetotelluric (MT) measurements in the CDR were focused on a large ( $\sim 50$  km<sup>2</sup>) area (Figure 5a). Previous SAGE results, including seismic refraction and reflection, modeled a thick ( $>2$  km) water-bearing sedimentary subsurface section with low-porosity, impermeable basement rocks below. SAGE student modeling of new, although sparse, gravity and MT measurements confirm depths of  $\sim 2$  km to high density/resistivity basement rocks (Figure 5b). The gravity model has a basement rise under the western part of the volcanic field (Figure 5b, in red). Uniform basement depths of  $B = 2.1$ – $2.3$  km (Figure 5c) were modeled below the four MT soundings on the eastern side of the volcanic field (Figure 5b, in red). An added geothermal finding from the MT modeling is the relatively shallow electrical mid-crustal conductor (MC  $< 15$  km). The depth to the ubiquitous MC in the western U.S. is considered to be a proxy for the depth of the  $500^\circ\text{C}$  isotherm (Wannamaker et al., 2008). SAGE results place this conductor at depths ranging from 27 km outside of the rift to 7 km deep under the Valles caldera, a world-class geothermal feature in the Jemez Mountains 15 km northwest of the Caja del Rio volcanic area (Figure 5a).

### Future of SAGE

Within the next two years we will be completing our study of the Pueblo San Marcos and are looking at the Piedras Marcadas, a historically and archaeologically significant site, as our next near-surface project. SAGE 2012 and 2013 will focus in understanding the geothermal potential of the CDR volcanic region using a combination of seismic, EM methods and gravity. To enhance ongoing geophysical research into the tectonics, faulting, and basin structure of the Rio Grande rift we will continue to expand our field area to new regions within the Rio Grande rift.

The SAGE faculty is changing. Although the emeritus faculty is still enthusiastically involved, our adjunct faculty are becoming more active. In 2010 we lost Bernie Gilpin, an original faculty member, to cancer. Bernie's smile, jokes and laughter, remembered by many, will be deeply missed. His memory will be captured in the annual SAGE Mental Attitude Award, known as "The Bernie." It will be given to the SAGE student who shows the ability to find the enjoyment and fun in work and daily life, and who displays positive mental attitude, leadership, determination, enthusiasm, and caring for others that enhance the quality of the SAGE experience. The 2011 Bernie was awarded to Michel Kordy from the University of Utah.

We will be celebrating our 30-year anniversary at the SEG Annual Meeting in November and at the December Fall



**Figure 5.** (a) Base map showing the location of the Caja del Rio area. (b) Complete Bouguer gravity anomaly and density model across the CDR volcanic field (red); location of four-station MT profile indicated by double-headed arrow. (c) Four east-to-west MT (transverse electric mode) sounding curves and corresponding 1D inversion results of depths to resistive basement (B) and mid-crustal conductor (MC).

AGU Meeting. We hope to see many graduates and friends of SAGE. If you are a SAGE alumni and have lost touch, please join the SAGE alumni group on Facebook or contact [braile@purdue.edu](mailto:braile@purdue.edu) or [pellerin@ak.net](mailto:pellerin@ak.net) and let us know where you are and what you are doing. If you are interested in attending SAGE, see <http://www.sage.lanl.gov>.

SAGE continues to have a bright future. Through the SEG Foundation (SEGF) an endowment has been established with founding donor Geophysical Pursuit, Inc. Establishing an endowment is a long-term endeavor that will ensure continuing funding, and we thank SEGF and Geophysical Pursuit for their support and generosity.

### Many thanks to our supporters

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The support of our generous sponsors includes loans of major equipment and industry-standard software, visits from working professionals, access to field sites and financial assistance. Currently they are:

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- Pueblo de Cochiti
- Santo Domingo Pueblo
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